BIO Web of Conferences **111**, 01003 (2024) https://doi.org/10.1051/bioconf/202411101003
ICBB 2024

Interactions between Crop and Microalgae in Nutrient Utilization in Crop- microalgae Co-culture

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Abstract. In order to conserve agricultural land and make the best use of environmental resources, scientists have developed hydroponic systems for growing crops and vegetables. At the same time, it has been found that microalgae and crops can interact on the basis of hydroponic systems. However, research on the nutrient utilization aspect of it is still very limited. In this paper, we investigate the nutrient utilization of crops and algae in a co-culture system, thereby contributing to the improvement of crop yields. Nutrient utilization in co-culture systems includes nutrient competition between crops and microalgae, the effect of CO_2 produced by crop roots on microalgae, the promotion of nutrient uptake by microalgae in crops and the stimulation of root growth, and the change in system pH induced by nutrient uptake in crops and microalgae. By analyzing these aspects, it plays a key role for both algae and crops to achieve higher yields and good growth conditions in the co-culture system.

1. Introduction

In many areas, the availability of fertile agricultural land is decreasing due to unfavorable soil or terrain conditions. At the same time, in such a severe environmental and climatic situation, scientists have proposed a new way of cultivation - hydroponics. This is a promising method of growing agricultural plants in closed greenhouses that are well insulated from external pests and diseases as well as climatic influences. At the same time to ensure crop yields through specific nutritional inputs can strengthen the crop and improve crop nutrition and qualitative characteristics, the full and reasonable use of greenhouse planting space can be better to create three-dimensional agriculture[1].

Microalgae are widely distributed and are found in terrestrial lakes, oceans and other waters. In recent years algae, especially microalgae, have been recognized in agriculture because of their ability to enrich carbohydrates, lipids, proteins and produce exogenous phytohormones. However, more than three-fourths of previous studies have focused only on cellular extracts of algae rather than the application of algal suspensions containing living cells to plants or soil systems[2]. Microalgae in the hydroponic environment in addition to a suitable aquatic environment can provide organic nutrients for the crop, but also the CO_2 produced by the crop roots as raw material for photosynthesis to produce O_2 to alleviate the pressure of the hydroponic crop root respiration, which for the growth of hydroponics plants has a lot of help, so microalgae and crop co-cultivation in recent years has become a new direction of research.

Many studies have shown good interactions between microalgae and crops, and in co-culture experiments microalgae resulted in more vigorous root growth and improved crop accumulation in tomatoes [3]. Highly reflective algae also reduce the release of greenhouse gases from rice cultivation by lowering soil temperatures and also increase the resilience of rice to climate change [4]. Biostimulants released by Chlorella during hydroponics promote the growth of cucumber roots and shoots, which is used in the nursery of hydroponically grown cucumbers [5]. In addition, the addition of microalgae to hydroponics has had a positive effect on the growth of a wide range of crops, e.g., corn, mint, sugar beets, spinach. Although co-cultivated crops grew better than normal hydroponic crops, the growth of algae in co-cultivated systems was not as good as in systems with pure algal cultures [6]. The highest crop biomass was achieved in the microalgae-free group in the arugula-microalgae co-cultivation experiment [7], suggesting that nutrient utilization interactions between crops and microalgae may be diverse due to the diversity of crop and microalgae species, the diversity of nutrients, and the complexity of the crop-microalgae interactions.

Determining crop-microalgae interactions in nutrient utilization is critical to understanding crop-microalgae interactions and successful management of crop-microalgae co-culture systems. In this study, theoretical considerations and literature assessment were used to identify possible aspects of crop-microalgae interactions in nutrient utilization in crop-algae co-cultures.

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2. Positive effects of microalgae on crops in Co-cultivation

The lives of people are filled with microalgae in various fields, whether in food additives, health products, cosmetics, fertilizers, or biodiesel. The role of microalgae in co-cultivation system will be multi-faceted, so this article from the following aspects to express the role of microalgae in co-cultivation system. In addition, microalgae also play an irreplaceable role in co-culture systems, especially for crop cultivation, which can provide the nutrients needed for its growth.

2.1. Organic nutrition

2.1.1 Direct effect on crops

Microalgae, as photosynthesizing microorganisms, can produce and accumulate a wide range of organic matter in a co-culture system, which can be released through life activities and material exchange. At the same time, as a microorganism, it has a rapid renewal rate. It also releases organic nutrients from its body when it dies and lyses. These contain many different types of lipids (structural and storage lipids), various fatty acids, carbohydrates, proteins, amino acids and their derivatives.

In addition to providing crop root cells with basic raw materials for biochemical reactions and cell membrane composition, crop seedling roots can regulate lipid metabolism in response to NaCl stress through differential gene expression [8]. Proteins absorbed by crop roots can be catabolized and participate in cell composition, and amino acids, as the basic building blocks of proteins and intermediates of other biochemical reactions, can directly promote crop growth and development [9], and also indirectly affect crop growth by synthesizing compounds and influencing the regulation of phytohormones [10-11].

From the "source," "reservoir," and "flow" doctrines, it is inferred that the roots of a crop act as a "reservoir" to receive the carbohydrates produced by the leaves as a "source" for use in the normal life activities of the root cells. "source" of carbohydrates produced by the leaves, which are used for the normal life activities of the root cells. Carbohydrates released by microalgae in the co-culture system can be directly absorbed by the root cells of the crop, reducing some of the transportation of carbohydrates in the crop and allowing more carbohydrates to be accumulated in the crop fruits, thus increasing the yield of the crop in the co-culture system.

2.1.2 Indirect effect on crops

Soilless culture constructs a protective cultivation environment for plants, which prevents many diseases and pests from infesting them. However, in hydroponic systems, it also provides good conditions for the growth of other disease-causing microorganisms, and their presence can also make hydroponic crops sick and affect crop accumulation. Chemical control is not feasible in hydroponic systems, as chemical fungicides act on microorganisms as well as crops, so biological control is the optimal choice. Microalgae in co-cultivation systems have the potential for biocontrol, as several microalgae have been shown to have anti-fungal, anti-bacterial, and anti-viral properties [12], and this antimicrobial effect can be used to better support crop growth in co-cultivation systems.

2.2. Inorganic nutrition

The inorganic salt ions required by the crop in the co-culture system will not be directly supplied by the microalgae, but the microalgae will also enrich the inorganic salt ions in the culture solution during the growth process and release them together with the organic nutrients in the co-culture system during death lysis. The addition of microalgae has also been shown to significantly increase the efficiency of N, P and K accumulation in hydroponic systems [13]. In traditional hydroponics, as crop roots are immersed in the nutrient solution for a long period of time, the dissolved O_2 in the system does not meet the needs of the roots. Roots, as the nutrient organs of plants, play a pivotal role in the growth process of crops, and the lack of O_2 in roots is fatal to crops. The O_2 produced by microalgae through photosynthesis is just enough to alleviate the lack of oxygen, while the CO_2 produced by root respiration can increase the soluble C pool in the nutrient solution, which can also be used as the raw material for microalgae photosynthesis [3]. Positive interactions between microalgae and crops also increase the rate of root respiration, providing sufficient energy for root uptake of nutrients [13].

2.3. Compare to traditional hydroponics

The concept of crop hydroponics has been proposed for many years, with a great deal of related research and partial commercialization. The application of hydroponics can avoid most of the yield reduction caused by climate, pests and viruses by practicing protected cultivation. At the same time, through the construction of three-dimensional agriculture can make better use of environmental resources to achieve crop yield increases, through statistics from 2017 to 2021 vegetable crops (cucumbers, peppers, fennel, coriander, etc.) hydroponics yields 1.19 to 2.63 times higher than soil agriculture [14]. Crop-microalgae co-cultivation systems not only utilize the advantages of traditional hydroponics, but the addition of microalgae can help crop growth in a variety of ways.

The characterization of the nutrient provisioning aspect in agricultural systems is known as Nutrient Accumulation Efficiency (NAE) and higher NAE is essential for co-culture systems and it was also clearly found through experiments that NAE was significantly higher in co-culture than in conventional hydroponic systems [13]. Crops in traditional hydroponic systems do not fully utilize the nutrients in the nutrient solution, and the addition of microalgae allows for better utilization of these nutrients and improves the self-cleaning ability of the co-culture system [7]. Microalgae can also be produced as a secondary product and the cost of cultivation can be reduced in terms of disease control and gas supply, thus further improving economic efficiency. With the addition of abundant biomass, the disposal of culture effluent can become cumbersome, and this is an area for further optimization in the future, to reduce pollution and better implement sustainable agriculture, and to better promote commercial co-cultivation systems.

3. Nutrient requirements and nutrient competition between crops and microalgae

3.1. Nutrient requirement

3.1.1 Nutrient requirements of crops

Crops have specific nutrient requirements in both soil and hydroponics situations that do not vary much. Further analysis of the nutrient solution formulations used in the study with those of the commonly used hydroponic Hoagland solution shows that most of the nutrient solution formulations used in the experiments were based on the Hoagland nutrient solution with improvements in the quest for a more suitable growing environment for the respective crops. For hydroponic crops, both massive elements (C, N, P, K, Ca, Mg, S, etc.) and trace elements (Mn, B, Mo, Cu, Fe, Zn, etc.) required for normal life should be added in hydroponic solutions as required.

The ratios between elements also need to be set appropriately, and it has been found that an imbalance in N and K fertilization can lead to chlorosis at the edges of the leaves and affect crop accumulation [15]. It is not only N and K fertilization that needs to be kept in a certain range of balance, with the proper proportions maintained between each element. In addition to this, the form of ions present in the nutrient solution also has an impact on crop growth; NH_4^+ and NO_3^- are two common forms of nitrogen, with many crops preferring nitrates, the exact form of which is still dependent on the preference of the person to whom the fertilizer is applied as well as environmental factors.

3.1.2 Nutrient requirements of microalgae

Microalgae contain macroelements (C, N, O, P, K, S, etc.) and microelements (Cr, Ca, Mg, Fe, Zn, Mn, etc.), which ensure their life activities. As in crop cultivation, the nutrient ratios need to be adjusted to the microalgae's preferences and the elemental forms need to be added in order to create a suitable environment for the microalgae to grow. Fichtbauer found that the microalgae had the highest biomass at N:P of 15:1 [16]. There was no significant difference between the ammonium and nitrate groups for growth rates of microalgae, but many microalgae preferred to take up ammonium nitrogen rather than nitrate, which was only used in the absence of ammonium. Instead, it was found that small doses of nitrogen ad libitum improved microalgal growth and lipid production [17].

3.2. Competition effect

3.2.1 Competitive situation

Since crops and microalgae are highly similar in terms of nutrient requirements, interspecific competition is theoretically bound to occur when cultured in the same system. The study did not show any significant competition, and on the contrary, the accumulation of the crop was enhanced [3,18]. However, in the results of the Özer Uyar experiment it was shown that the bioaccumulation of the control group, which was cultured only with microalgae, was higher than that of the microalgae in the co-culture system [6,13]. Inoculation of microalgae for co-cultivation at the time of crop seedlings can lead directly to seedling mortality [3].

3.2.2 Analysis and forecasting

There was no significant nutrient competition in the results of the experimental study of crop-microalgae co-cultivation, which may be attributed to the fact that the culture solutions used in the experiment were based on modified Hoagland's solution. The nutrient content of the solution was rich enough to satisfy the growth requirements of both microalgae and crops. The addition of microalgae increased the nutrient removal rate of the hydroponic system to a certain extent [7], but there is still an excess of nutrients which means that there is still room to reduce the cost of wastewater treatment at a later stage. The current level is not very precise to find out the formulation of the culture solution with the highest nutrient utilization, and in the future, through the accumulation of a large number of experimental results can be close to the range of the optimal culture solution, which can still be used as a direction for future research on the co-culture system.

The presence of the phenomenon of nutrient competition does not necessarily imply negative feedback for the crop; minor nutrient competition does not inhibit crop growth [6,18]. Instead, the crop's root growth is promoted due to the adversity stress, which enhances nutrient uptake by the root system. The intensity of nutrient competition produced by different species of microalgae is different [13], as is the intensity of nutrient competition produced by the same species of microalgae at different concentrations. One of the most central parts for the successful setup of a crop-microalgae co-culture system is to ensure that the crop is the dominant competitive species in the system [18]. Too low a concentration of microalgae in a co-culture system will not promote the crop significantly, and too high a concentration added will affect the normal growth of the crop. Therefore, the success of a co-cultivation system needs to ensure the compatibility between microalgae and crops, and the concentration of microalgae in the co-cultivation system should be controlled in a way that it can promote the crops and at the same time, not to take over the dominant position of the crops in the co-cultivation system. The co-cultivation of newly germinated crop seedlings with microalgae is precisely due to the incomplete development of the root system of the crop during the seedling period and the weaker nutrient competition ability than that of the microalgae, which leads to the slowing down of the development of the seedling, stagnation or death of the crop seedlings. Usually, newly germinated seedlings are first cultivated individually, and then co-cultivated with microalgae after they have some nutrient competitiveness and are able to maintain a competitive advantage in the system.

4. Effect of PH on the Co-culture system

4.1. Effect of PH on Nutrients in Co-culture system

The effect of pH on the liquid environment is huge, especially in nutrient solutions rich in many nutrients. Wang found that most of the nutrients were directly affected by the pH of the system except Mn [19]. For nutrients such as Mg and Ca, which produce precipitation when combined with OH^-, pH > 7 resulted in the immobilization of these elements, and the reduction of free elements inhibited the growth of microalgae and crops in the co-cultivation system. Fe^{3+}, which combines with OH^-, triggers agglomeration and precipitation in the ion-rich medium, causing more nutrients to precipitate, and adsorbing to the root surface during the immobilization process, reducing the effective root uptake area. The combination of Fe3+ with OH^- in this ion-filled culture solution will lead to aggregation and precipitation, which will cause more nutrients to precipitate and adsorb on the surface of the crop roots during the immobilization process, reducing the effective absorption area of the roots. Accompanied by the precipitation of some ions, the original ionic ratio in the co-culture system will be broken, which will have a series of effects on the growth of microalgae and crops in the system [15]. For nutrients such as proteins, which have a spatial structure, too high or too low a pH will denature them and cause them to lose their original function. PH < 5 inhibits the adsorption of elements such as N, P, K, Ca, Mg, and Mo [20].

Changes in pH also trigger changes in a variety of ionic equilibria within the co-culture system, with the most pronounced changes being in the CO_2-HCO_3^- and NH_3-NH_4^+ equilibria in the culture system [16]. Decreased CO_2 levels can inhibit photosynthesis in microalgae, while increased NH_4^+ levels can be toxic to crop roots. The pH value in the co-culture system tends to change with the growth and population competition between the crop and microalgae, and it was found that the crop would cause changes in the pH value when absorbing N and P [21].

4.2. Effect of PH on microalgae and crops

Changes in pH value will not only affect the form and structure of nutrients in the nutrient solution, but also affect the ability of crops and microalgae to absorb nutrients. The optimal pH environment for most crops is around the neutral range, but the suitable pH environment for microalgae varies greatly, and some microalgae are able to survive in more severe environments, and it has been found that microalgae have higher CO_2 fixation rate and lipid accumulation in alkaline environments [22]. The results of the research experiments showed a negative correlation between changes in pH of hydroponically grown crops and the uptake of Zn, which affects the content of photosynthetic pigments [23].

4.3. Control and regulation

4.3.1 Control of PH Value

After successful operation of a co-culture system, it is impractical to try to maintain the ideal pH range all the time. Most experimentalists, when confronted with the problem of how to control pH, choose to replace the culture solution with a new one, but this undoubtedly generates a lot of culture wastewater, which is a big expense for the commercialization of the co-culture system. Until there is a stage of progress in controlling pH, steps should be taken in other areas. Determine a suitable pH range for the co-culture system by combining the appropriate growing conditions for the microalgae and the crop, and set up regular monitoring of the co-culture solution using a pH meter at regular intervals during the operation of the co-culture system. Adjustment is required once it is above or below the calibrated range. Control can take the form of direct replacement of the nutrient solution or chemical adjustment of the pH.

4.3.2 Adjustment of PH value

For pH changes in a co-culture system, regulation is not necessary within the normal range, but human intervention is required when it approaches the boundaries of the set range. Typically, organic acid and inorganic acids/bases are used as regulators and are dosed to regulate the pH of the co-culture system, which is essentially a neutralization reaction between H^+ and OH^- to regulate the pH of the system. When the regulator is added to the co-culture system, the non-regulating ions added along with the regulator will also participate in the nutrient cycling in the system. Therefore, ions that have a high impact on microalgae and crops should not be selected. At the same time, the addition of regulators will also bring nutrient uptake pressure on the crop, so the pH should be adjusted appropriately.

5. Conclusions and outlook

Research on crop-microalgae interactions in crop-microalgae nutrient utilization is still very limited. Microalgae can provide a wide range of organic nutrients to crops, and their bacteriostatic and antiviral abilities can also be of considerable help to crops. The CO_2 produced by root respiration increases the soluble C pool in the nutrient solution, which also serves as a raw material for microalgae photosynthesis. All these are not available in traditional hydroponic systems. Two species in the same culture system have highly overlapping nutrient requirements but there is little competition for nutrients because of the nutrient richness of the culture solution. Although microalgae can increase nutrient utilization in the system to some extent, there is still room for further research, and excessive unutilized nutrients can increase the pressure on wastewater treatment. Specifically, newly germinated crop seedlings are not suitable for co-culture with microalgae due to nutrient competition from microalgae. Changes in pH are often overlooked in the operation of a culture system, as under normal circumstances pH does not change drastically, but rather slowly over a long period of time. There is no simpler and more efficient way to control pH than regular long-term monitoring and the use of organic acid and inorganic acids/bases as regulators. The effects of large changes in pH on crop-microalgae co-cultivation systems have not yet been studied.

Crop-microalgae co-cultivation has been studied for a very short period of time, and the accumulated research results are very limited. By collecting and evaluating the relevant literature in recent years, in-depth research can be carried out in the following directions in the future. Firstly, the population of microalgae is very large, and there are many different co-cultivation combinations for different crops, from which the group with the greatest co-cultivation benefit can be selected (the workload in this direction should be very large). Secondly, the timing of co-cultivation of crops with microalgae should be optimized, as well as the range of concentrations of microalgae that should be added and subsequently controlled. In addition, the nutrient requirements and ratios of the co-cultivation system should be further investigated. In addition to this, the effect of changes in pH on the overall system and whether there are more efficient ways to control and regulate it. Finally, other directions that can reduce the cost of the system (new cultivation devices, reduction of wastewater disposal costs, etc.) will be further investigated. Overall, the research in the direction of crop-microalgae co-cultivation has not accumulated much, but the prospects for this novel culture scheme are promising. There is still a long way to go for the subsequent commercialization process, and it is possible to reach a certain height through subsequent supplementation.

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